

# Diatom distribution in the Weddell Gyre region during late winter

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**ABSTRACT:** Diatoms from the water column and sea-ice were analyzed in a data set collected from the Soviet icebreaker MIKHAIL SOMOV in late austral winter (October–November) 1981 in the Weddell Gyre region. Two major diatom assemblages are apparent in the water column and have distribution patterns that are influenced by surface and near-surface water hydrography (0–100 m). An assemblage dominated by *Nitzschia kerguelensis* is associated with typical Weddell Deep Water (WDW), while most warm-water cells within the WDW are associated with an assemblage dominated by *Thalassiothrix antarctica*. Sea-ice cores usually contain a surface assemblage dominated by *Cylindrotheca closterium*, a neritic form, underlain by *N. kerguelensis*- and *T. antarctica*-dominated assemblages. The diatom stratigraphy in these cores and the nature of the assemblages suggests that the surface form, *C. closterium*, has grown in place while the *N. kerguelensis*- and *T. antarctica*-dominated assemblages were frozen into the ice. It is hypothesized that, as the winter progressed, these latter two assemblages were sequentially frozen into sea-ice, thus leaving a record of gross oceanographic changes that occurred in surface waters beneath the ice during the austral winter.

## INTRODUCTION

Diatoms from sea-ice and the underlying water column (0–100 m) taken by the Soviet icebreaker MIKHAIL SOMOV during October–November 1981 (Joint U.S.-U.S.S.R. Weddell Polynya Expedition or WEPOLEX) were examined. The objectives, to analyze the later winter diatom populations within the seasonal sea-ice zone as well as within an active open ocean polynya, were only partially met. No polynya developed during the winter of 1981. However, a reasonably good sample coverage allowed description of the late winter geographic distribution of diatoms in the water column as well as comparison with those in the overlying sea-ice.

Locations of water column stations used for diatom analysis are given in table 1<sup>1</sup> while other pertinent data (ship's track, CTD [Conductivity, Temperature, Depth]-oxygen/Rosette hydrographic stations, XBT [Expendable Bathythermograph] observations, sea-ice core sites and position of the ice edge at time of entry and exit) are given in Gordon and Huber (1984) and Marra and Boardman (1984). The sampling area extended to almost 600 km south of the October ice edge, with the first water column station taken well within the pack ice and the last station taken near the ice edge. Additional data on the physical setting of the Weddell Sea in winter 1981 (time of freeze-up, waxing and waning of sea-ice and physical oceanography) are given by Gordon and Huber (1984).

Diatoms in sea-ice of the Southern Ocean were first described by Hooker (1847) who reported that rapidly formed sea-ice contained abundant diatoms. Vanhoffen (1903) described part of the seasonal cycle for diatoms living in sea-ice and pointed out that initial development of the population began in November with an assemblage that was usually monospecific. As the ice melted, these forms were released into the water column and mixed with other planktonic forms. Gran (1931) and Hart (1934) discussed the effect of sea-ice

on diatoms and Hart (1934) noted that diatom spores in ice may reflect a "wintering-over" strategy which may account for the abundant flora found along the edge of the retreating pack ice in spring.

Modern studies on sea-ice diatoms have stressed experimental, community and laboratory analyses. Most of these studies are reviewed in Horner (1976, 1985). Palmisano and Sullivan (1982) investigated the response of three Antarctic sea-ice species to a simulated "fall/winter" transition. Over this transition, they found a decline in growth rate, and a decrease in cellular ATP (adenosine triphosphate) accompanied by storage and later utilization of endogenous carbon reserves. In spite of these survival strategies, less than 10% of the clones survived the "winter."

Little *in situ* work has been done on diatoms in the water column of the Southern Ocean during the austral winter. Vanhoffen (1903) and Hart (1942) reported low numbers of diatoms in the water column during October and November, the earliest months for which they had data. Krebs (1977) reported that primary productivity was negligible in Arthur Harbor during the austral winter because of insufficient sunlight and because mixing in the water column carried many of the diatoms below the critical depth. Ferreyra and Tomo (1978) reported total diatom counts in the water column in Paradise Bay as low as 21 cells per liter during the winter compared with values in excess of two million cells per liter during the summer. Our sampling period came between these two extremes; it included the low productivity winter period but also the very early spring bloom near the ice edge.

According to Gordon and Huber (1984), the track of the MIKHAIL SOMOV was largely within the trough of the cyclonic Weddell Gyre, a region which is characterized by the cold Weddell Deep Water. The northern stations are within the northeastward flowing limb of the Weddell Gyre but the northernmost ones (on the northbound track) fall outside of the Gyre and are within Circumpolar Deep Water. To the south of the MIKHAIL SOMOV track is the south-

<sup>1</sup>All tables are on file with the author.

westward flowing limb of the Weddell Gyre, which is also referred to as the Weddell Deep Water. This limb is warmer than the eastward flowing limb to the north and is largely derived from Circumpolar Deep Water near 20–30°E (Gordon and Huber 1984; Gordon et al. 1984). An abrupt transition occurs, however, to the west of Maud Rise where there is a return to the Weddell cold regime.

Along the MIKHAIL SOMOV track, and within the Weddell cold regime, Gordon and Huber (1984) noted the presence of warm cells of Weddell Deep Water. Water in these cells is warmer, saltier, and has a higher oxygen content and a shallower pycnocline than surrounding water from corresponding depths. Gordon and Huber (1984) concluded that instability along the frontal zone separating the relatively warm water of the Weddell Gyre inflow (southwest flowing) from the cold water of the Weddell Gyre outflow (northeast flowing) injects warm Weddell Deep Water into the cyclonic trough of the Weddell Gyre. Eventually, the excess heat and salt of these cells enters surface waters. That this process influences faunal distribution is suggested by the work of Morley and Stepien (1984), who reported that polycystine radiolarians are more abundant in the warm-water cells than in the surrounding cold water. Two warm-water cells were reported along the southbound track of the MIKHAIL SOMOV and two are present along the northbound track. It is likely that the cell on the southbound track is the same as the southernmost cell on the northbound track (see Gordon and Huber 1984, fig. 2).

## METHODS

Water column samples were collected in 8-l Niskin bottles, usually at depths of 0, 25, 50 and 100 m (see table 1). Particulates in the water samples were concentrated on Millipore filters (0.8 µm pore size). These filters were gently washed to remove the residue, and permanent slides were made after the method of Schrader (1974). Paired ice cores were usually taken at each site using an 0.076-m diameter CRREL (Cold Region Research and Engineering Lab) ice coring auger. Where possible, three or four samples for diatom analysis were taken of each core pair to make up a composite section. Ice samples (volume ranging from 30 to 300 ml) were melted down at room temperature, diluted with distilled water and made into slides following the same technique as that used for the water column samples.

Diatoms were counted and identified to the species level in all samples. Where there were sufficient diatoms, 300 specimens were counted. These were analyzed by Q-mode factor analysis using procedures described by Imbrie and Kipp (1971). Three data sets were treated: diatoms in the water column, diatoms in sea-ice and diatoms in both the water column and the sea-ice. In addition, a ratio of whole to fragmented (W/F) diatoms was determined for each sample as was the total diversity (Shannon-Wiener) within each assemblage. All these data were compared with a measure of numbers of diatoms per unit volume (expressed as diatoms per liter in water column samples and diatoms per 100 ml in ice samples). Finally, a ratio of centric to pennate diatoms was determined. Some of these measures proved to have limited value, at least within the context of this data set.

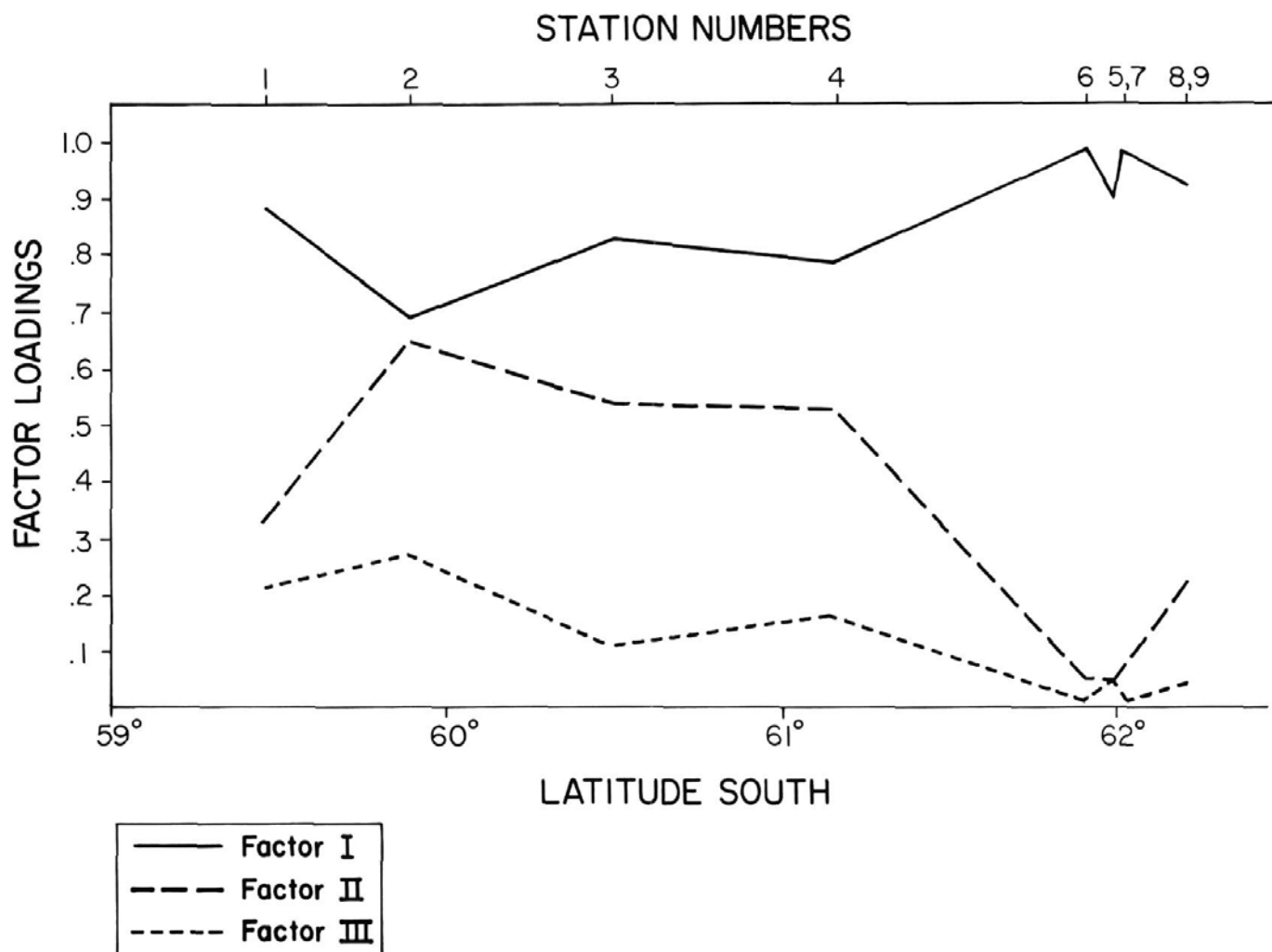
## THE DATA

### Water column

Three diatom factors were identified in the water column, of which two are considered major (table 2). Factor I accounts for 49% of the variance and is dominated by *Thalassiothrix antarctica* (Schimper) Karsten with lesser occurrences of *Nitzschia kerguelensis* (O'Meara) Hasle, *N. curta* Hasle and *Thalassiosira gracilis* (Karsten) Hustedt (table 2; text-figs. 1, 2). *Thalassiothrix antarctica* has a wide occurrence in the Southern Ocean but is more abundant in the subantarctic region, north of the Polar Front (Hendey 1937; Hargraves 1968). Factor II, which accounts for 45% of the variance, is dominated by *N. kerguelensis*, but *Nitzschia angulata* Hasle, *N. curta*, *Thalassiosira lentiginosa* (Janisch in Schmidt) Fryxell and *T. gracilis* are also common. *Nitzschia kerguelensis* is one of the more common planktic species in the Southern Ocean, both in the water column (Hendey 1937; Fenner et al. 1976) and in the underlying surface sediments (Abbott 1974; DeFelice and Wise 1980; Burckle 1984). Indeed, both Hendey (1937) and Fenner et al. (1976) have suggested that there is only one major summer diatom assemblage in open waters of the Southern Ocean, dominated by *N. kerguelensis*. Burckle (1984) found three diatom factors in surface sediments of the Southern Ocean but noted that the *N. kerguelensis* factor was dominant.

Factor III (3% of the variance) has highest values for *Thalassiosira gracilis* but there are also common occurrences of *N. angulata*, *N. curta*, *T. lentiginosa* and *Tropidoneis* sp. This is the only assemblage with significant numbers of centric diatoms. All three factors are characterized, for the most part, by species which are also preserved in the sediment record. The major exception is the delicate form *Tropidoneis*, which is generally not present in any recognizable state in bottom sediments. As mentioned previously, *Thalassiothrix antarctica* is reported to be more common north of the Polar Front. An assemblage dominated by this form is therefore considered to represent a "warm water" assemblage. *Nitzschia kerguelensis*, on the other hand, increases in abundance toward the Polar Front and south of it and is considered a "cold water" form. This relationship is supported by a number of other studies (Hendey 1937; Fenner et al. 1976; Burckle 1984; Burckle et al. 1987).

Text-figures 1 and 2 show factor loadings for the three assemblages on the southbound (text-fig. 1) and northbound (text-fig. 2) track. Between Biostations 2 to 4 (Text-fig. 1), Factors I and II co-dominate, and Factor III is present only as a minor component. North of Biostation 2 and south of Biostation 4, however, loadings for Factor I go above 0.9. They stay above that level between Biostations 6 and 10. The northbound track (text-fig. 2), shows a sharp drop in Factor I loadings (to <0.3) north of Biostation 10. Within a short latitudinal span (between Biostations 11 and 12), Factor III reaches loadings as high as 0.6, the only point in the track where this factor reaches any importance. Factor II dominates in the remaining Biostations 13 to 17 (text-fig. 2). The warm Weddell Deep Water cells occur at Biostations 5–9, and Biostations 10 (text-fig. 2) and 13. Likely, the warm cell at Biostations 5–9 and 10 represent the same feature (see Gordon and Huber 1984, fig. 2).



TEXT-FIGURE 1

Factor scores (loadings) for diatoms in near surface water samples along the southbound track of MIKHAIL SOMOV. Loadings for Factors I, II and III are read on the left side of the diagram while station numbers relative to degrees of latitude are read from the top and bottom, respectively.

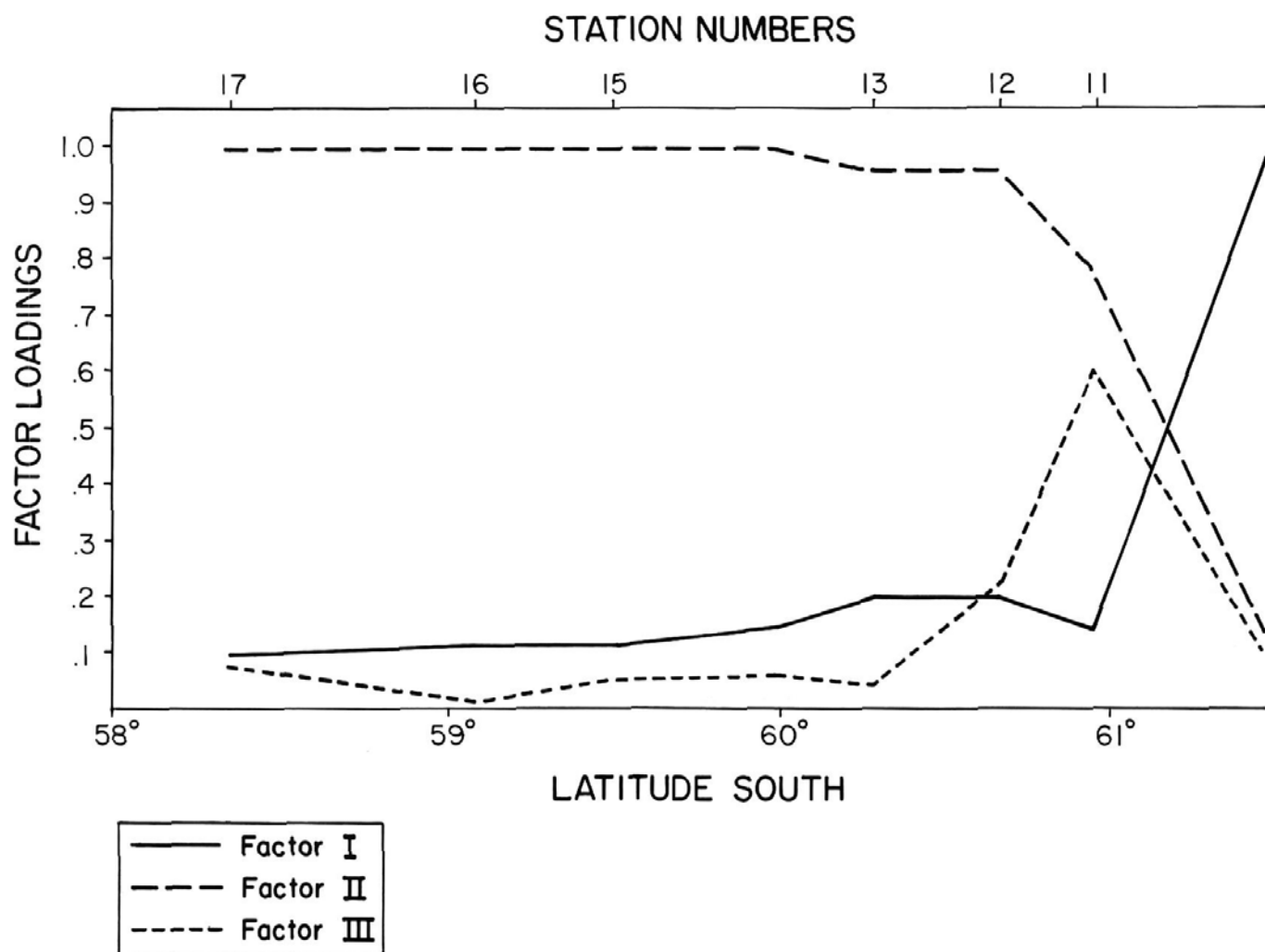
Other measures (diversity, breakage, numbers of cells per unit volume, pennate/centric diatom ratio and ratio of biogenic to nonbiogenic particles) were also made on diatoms in the water column. The Shannon-Wiener diversity equation

$$H_s = - \sum_{i=1}^s p_i \log p_i$$

(where  $H$  = diversity of  $s$  species in the group and  $p$  = relative proportion of the  $i$ th species, measured from 0–1.0) was used and a simple ratio of whole to fragmented diatoms (W/F) was determined. These measures tended to have more meaning for the water column (where a more complete set of samples was recovered) than for sea-ice. The W/F remains low at most of the biostations. However, in Biostations 9 and 10, the W/F goes unusually high (above 3 in Biostation 10), probably a reflection of the intrusion of a warm-water cell. In general, W/F is low and diversity is high along most of the track. At the southern limit of the track, however,

where the *T. antarctica* factor (Factor I) dominates, the situation is reversed with low diversity and high W/F.

A different pattern is evident in the ratio of pennates to centrics and biogenic to nonbiogenic particles. Along most of the track, pennate diatoms are much more numerous than centrics. The only place where this is not true is at Biostations 11 and 12 where Factor III, with such centrics as *Thalassiosira gracilis* and *T. lentiginosa*, increase in importance. Changes in the biogenic/nonbiogenic ratio probably reflect the onset of the austral spring. Along the southbound track, nonbiogenic particles predominate, frequently making up 95–99% of all particles in the water column. This ratio is somewhat different on the northbound track until at the most northerly station (Biostation 17), it reaches 0.81, likely reflecting increased biological productivity at the ice edge. This picture is supported by a calculation of numbers of diatom cells per liter. Near the ice edge (at Biostation 17) there are close to a million cells per liter while at stations beneath the



TEXT-FIGURE 2

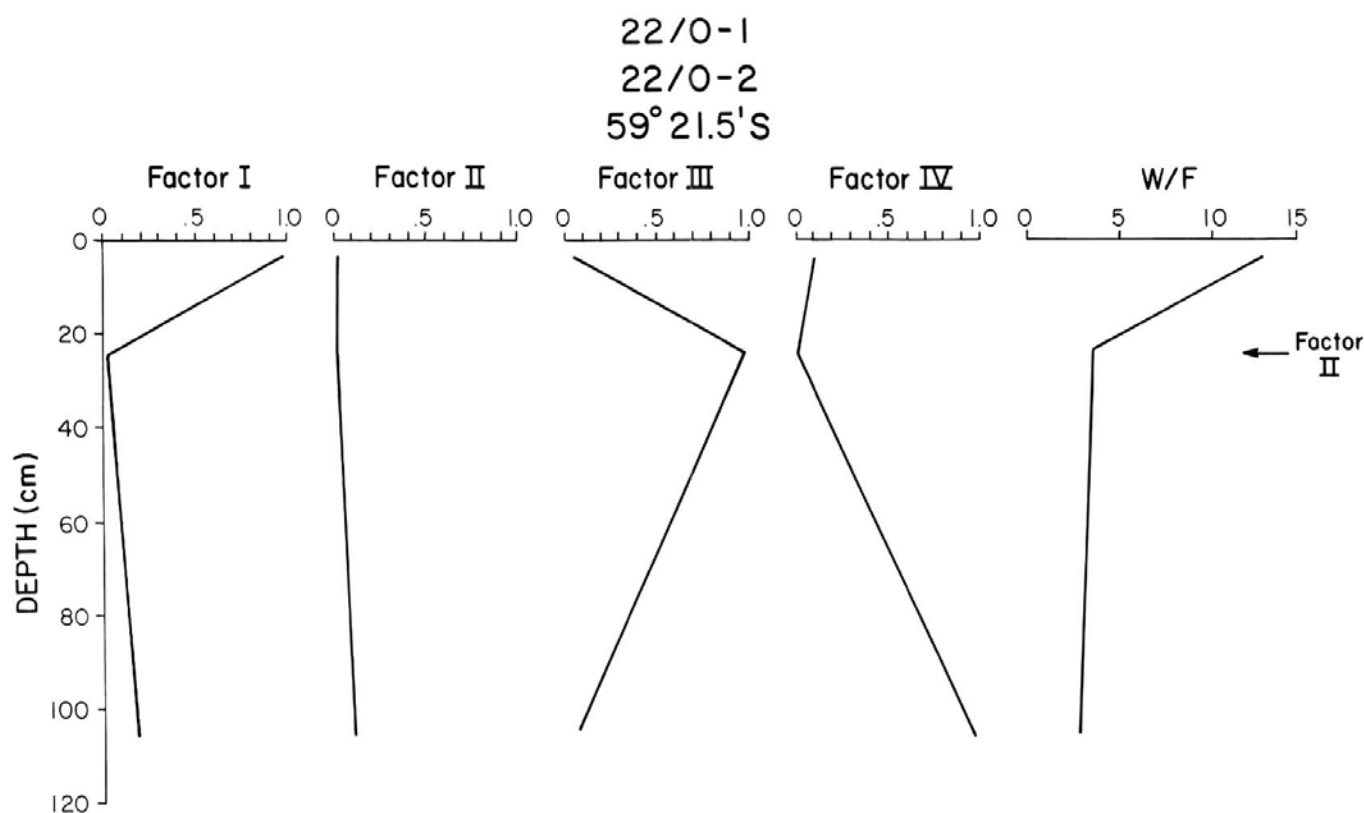
Factor scores (loadings) for diatoms in near surface waters on the northbound track of MIKHAIL SOMOV. Loadings for Factors I, II and III may be read along the left side of the diagram while station numbers relative to degrees of latitude are read from the top and bottom of the diagram, respectively.

ice to the south, values are a quarter to a fifth as high. Whitaker (1982) reported that around Signy Island the beginning of diatom growth may be retarded by persistent fast-ice and that total production under the ice is small compared with that of the open water.

#### Sea-ice diatoms

Because of the various demands on sea-ice samples, only a limited number were available for diatom analysis. A total of 18 samples were analyzed, but frequently these represented only one or two samples from a single ice core. Since two cores were usually taken at each site, all samples from one site were combined to make up a composite section for that site. Using this approach, three composite sections were constructed for illustration and discussion (text-figs. 3-5). These sites are all near the prime meridian and range in latitude from 59 to 62°S.

All samples were counted for diatoms and the raw data reduced by Factor Analysis (Imbrie and Kipp 1971). Four diatom assemblages are recognized, two of which are unique to the sea-ice, at least within this data set. Factor I (accounting for 29% of the data) is almost monospecific with *Cylindrotheca closterium* as the dominant species. This factor occurs in the upper part of the ice column and is characterized by low diversity and high W/F (up to 20). *Cylindrotheca closterium* is widely distributed in today's oceans (Cupp 1943; Hendey 1964; Reichert 1975) but occurs most abundantly in mid-latitudes during the winter. Hendey (1964) reported that it forms thick mats in coastal waters around the British Isles in winter. In the Southern Ocean, Hasle (1969) observed highest concentrations of this species in the water column in the far south as did Hart (1942), Boden (1949), Marumo (1957), Fukase (1962), Cassie (1963) and Krebs (1977). Krebs (1977) and Krebs et al. (in press), among others, observed this species in near-shore sea-ice. Richardson and Whitaker



TEXT-FIGURE 3

Scores for four diatom factors in composite sea-ice core 22/0-1 and 22/0-2. W/F (whole to fragmented diatom) ratio is given to the right. On the extreme right, the level in the core at which sea-ice Factor III is similar to water column Factor II is given.

(1979) reported dense concentrations of *C. closterium* and *Navicula glaciei* Van Heurck in infiltration ice (i.e. ice formed when snow is soaked with sea water either by flooding of snow-capped sea-ice or by sea water splashing over snow-capped floes). Infiltration ice is solid but porous and resembles a benthic type of habitat (Richardson and Whitaker 1979).

Factors II and III (22% and 21% of the variance, respectively) in the sea-ice are of special interest because they are nearly identical to water column Factors I and II (tables 4 and 5). In those core pairs, Factor II (the "warm water" *Thalassiothrix antarctica*-dominated factor) occurs stratigraphically above Factor III (the "cold water" *N. kerguelensis*-dominated factor). Factor IV usually occurs near the base of the ice cores and contains abundant specimens of *Tropidoneis*. This genus can be cryoplanktonic (Krebs 1977) while Burckle et al. (1987) recorded it in abundance in surface waters adjacent to sea-ice in the Ross Sea.

There is good correlation between high factor loadings for Factor I and high W/F values. As shown in text-figures 3-5, the W/F ratio is consistently high in the presence of Factor I. Diversity is low in this factor, generally tending to be higher in the other factors. The total number of diatom cells (expressed as the number of cells per unit volume) was also determined for each sample. Here, no definite trends are established but there do appear to be some tendencies in the

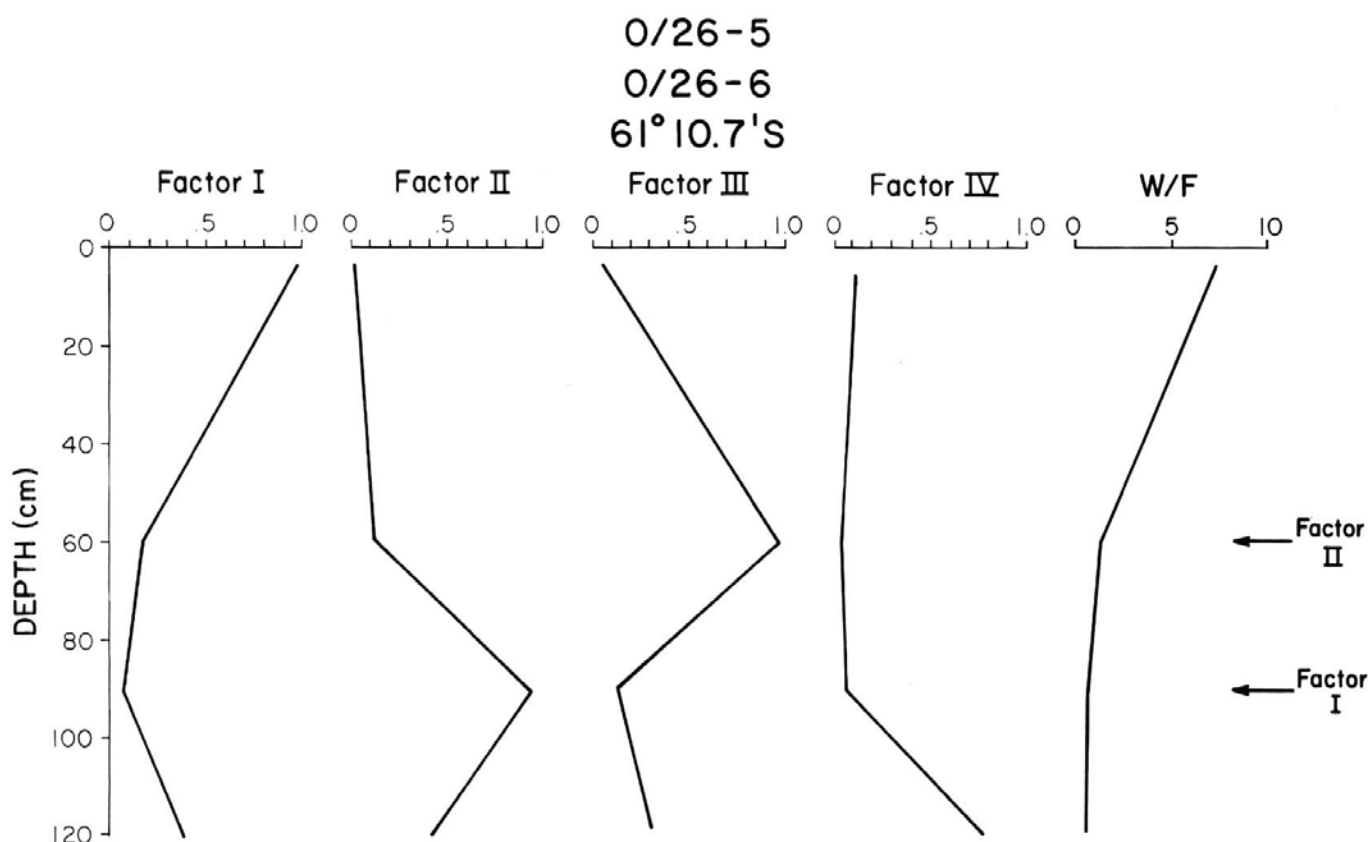
data. In general, cell counts are lower in surface and near surface samples and higher in the lower and middle part of the ice cores.

#### DISCUSSION

Gordon and Huber (1984) reported the presence of warm sub-surface eddies of Weddell Deep Water with properties similar to those of the Weddell Gyre inflow. They hypothesized that gyre "spin-up" sometime during the winter, accompanied by instability within the frontal zone that extends from Maud Rise to the northeast, allowed the Weddell inflow regime to inject warm Weddell Deep Water cells into the gyre trough. However, they could not rule out the possibility that all or some of the warm-water cells were injected from the Weddell Gyre/Circumpolar Deep Water Front. The Radiolaria distribution (Morley and Stepien 1984) reflects the injection of these warm-water cells but cannot designate the source.

The diatom data also appear to reflect the injection of warm-water cells as well as the influence of the Circumpolar Deep Water. The increased factor loadings for the *Thalassiothrix antarctica*-dominant ("warm water") assemblage appears to be due to the injection of warm-water cells from the southwest flowing Weddell inflow regime. High factor loadings for this assemblage occur at Biostations 1, 5-9 and 10, coincident with those hydrographic stations where Gordon and Huber





TEXT-FIGURE 4

Scores for four diatom factors in composite sea-ice core 26/0-5 and 26/0-6. W/F (whole to fragmented diatom) ratio is given to the right. The levels at which sea-ice Factors II and III are equivalent to water column Factors I and II, respectively, are given.

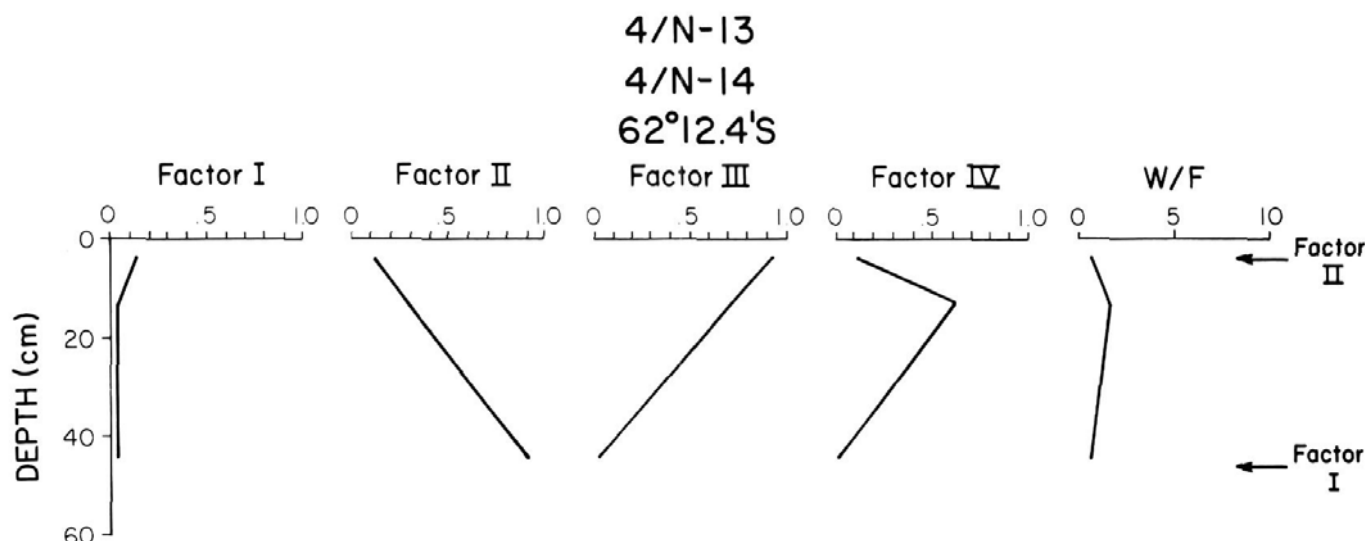
(1984) reported warm-water cells. At other sites along the northbound track, however, the warm-water cells do not carry a correspondingly "warm water" assemblage. Specifically, Biostations 13 and 17, which overlie warm-water cells, have a "cold water" *Nitzschia kerguelensis*-dominated assemblage.

The assemblage at Biostation 17 can be accounted for because it was recovered from north of the Weddell Gyre/Circumpolar Deep Water Front. Burckle (1984) has shown that an *N. kerguelensis*-dominated assemblage is characteristic of both the Circumpolar Current and the northeast flowing limb of the Weddell Gyre. Hendey (1937), Fenner et al. (1976) and Burckle et al. (1987) reported that the Austral summer waters of the Southern Ocean, exclusive of neritic areas, are dominated by this species while Hart (1942) referred to *N. kerguelensis* as the most abundant diatom in the Southern Ocean when averaged over the year. Similarly, Cirilli (1982) found this species dominant in surface sediments of the Pacific sector of the Southern Ocean as did Burckle (1984). Since *N. kerguelensis* is the dominant form overlying the warm-water cell at Biostation 13, this cell may represent the alternate possibility proposed by Gordon and Huber (1984), i.e. that it was injected from the northwest, along the Weddell Gyre/Circumpolar Deep Water Front, rather than from the Weddell inflow current to the southeast. I am unable to account for high loadings for Factor III (*Thalassiosira gracilis*-

dominated assemblage) at Biostation 11. It occurs between a warm-water cell, which originated from the southeast and one which we presume originated from the northwest.

According to satellite photographs, sea-ice was formed in the WEPOLLEX study area during June–July 1981. Although late in the season, it is still not too late for significant numbers of phytoplankton to be present in the water column (though certainly not in the numbers encountered during the Austral Summer). If an *N. kerguelensis* assemblage was present in the Weddell region in June–July (published data show that such an assemblage persists through the Austral Summer), then it would have to be the first assemblage frozen into the newly formed sea-ice.

As the winter progressed, an increase in the curl of the wind stress would spin-up the Weddell Gyre and draw warm-water cells into the trough of the gyre (Gordon et al. 1981). As noted previously, a *Thalassiothrix antarctica*-dominated assemblage is associated with most of these warm-water cells. Continued sea-ice formation as the "warm water" cells are injected into the gyre trough would result in the freezing in of the *T. antarctica*-dominated assemblage. Thus, the record of the previous winter—initial freeze-up, and injection of warm-water cells is preserved in the sea-ice record. The physical basis for this scenario is supported by the work of Garrison et al. (1983) who proposed ice nucleation and subse-



TEXT-FIGURE 5

Scores for four diatom factors in composite sea-ice core 4/N-13 and 4/N-14. W/F (whole to fragmented diatom) ratio is given to the right. On the extreme right the levels at which sea-ice Factors II and III are equivalent to water column Factors I and II, respectively, are given.

quent scavenging as the mechanism by which diatoms are incorporated into sea-ice. They also point out that changes in the character of the underlying water mass would result in different diatom species being frozen onto the underside of the sea-ice.

As noted previously, *Cylindrotheca closterium* (in Factor I) occurs in abundance in infiltration ice along with *Navicula glaciei*. Further, the character of this assemblage, its low diversity, high W/F ratio and the absence of *C. closterium* from the underlying sea-ice and water column strongly suggests that it had undergone a number of doublings while in the sea-ice during the winter months. Our data also suggest that increased numbers of this species, at least in this data set, is associated with snow that was flooded by sea water and frozen into the upper layers of sea-ice. Fairbanks (pers. comm.) did oxygen isotope analyses of selected sea-ice samples from this data set and noted that, in samples where *C. closterium* is abundant, the sea-ice is isotopically light, indicating an input of up to 35% fresh water (via precipitation). In those samples with abundant *Nitzschia kerguelensis* or *T. antarctica* oxygen isotope analyses indicate that the sea-ice largely consists of frozen sea water.

Factor IV is dominated by *Tropidoneis* sp., species of which occur in both sea-ice and adjacent water column (Krebs 1977; Burckle et al. 1987). In most samples examined here, this assemblage occurs near the base of the ice column, although in the most southerly site it is found in the middle of the ice column. I am unable to offer an explanation for these occurrences.

The record of warm-water cell injection into the Weddell Gyre trough is not only recorded in the winter water column and the overlying sea-ice but in the underlying surface sediments as well. Burckle (1984) studied diatoms in surface sediments of the Weddell region and found an *N. kerguelensis*-dominated assemblage beneath the northern edge of the Weddell Gyre and a warmer water assemblage beneath the

gyre trough. That this is a more or less permanent feature of the Weddell region is supported by the fact that Burckle and Labeyrie (in prep.) found a similar relationship in sediment believed to represent the Last Glacial Maximum (18,000 yr BP).

## CONCLUSIONS

Major hydrographic features in the Weddell Gyre in late winter are reflected in the distribution of diatoms in surface waters. The same general pattern is also recognized in diatoms in the underlying surface sediments and in sediments from the Last Glacial Maximum. In the overlying sea-ice, a definite diatom stratigraphy can be discerned in undisturbed sections. This stratigraphy can be used to decipher, in part, the history (record of "warm water" injection events) of the previous winter. Obviously more work needs to be done, in particular, baseline studies comparing diatom distribution in the water column in winter with surface and near surface hydrography. It seems, however, that sea-ice is amenable to geological/biostratigraphic studies and that Huttonian principles can be applied.

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